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The Validation Archive of the NPARC Alliance

Kenneth E. Tatum
Sverdrup Technology, Inc., AEDC Group
Arnold Engineering Development Center
Arnold Air Force Base, TN 37389

John W. Slater
NASA Lewis Research Center
Cleveland, OH 44135

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Kenneth E. Tatum†
Sverdrup Technology, Inc., AEDC Group
Arnold Air Force Base, Tennessee
and
John W. Slater‡
NASA Lewis Research Center
Cleveland, Ohio

Abstract

The NPARC Alliance provides a publicly available, Internet-based archive of analytical, experimental, and computational data suitable for validation of computational fluid dynamics (CFD) codes. The primary objective of the Archive is validation of the WIND code, the primary CFD solver of the Alliance, and making the validation results available to the CFD community at large. The secondary objective is to provide the aerospace community a forum for CFD validation efforts. This paper discusses the Validation Archive in general. It presents an overview of the validation policies of the Alliance, the structure of the Archive, and the processes for performing validation studies. A few selected cases are presented as samples of the validation effort.

Introduction

The NPARC Alliance is a partnership between the USAF Arnold Engineering Development Center (AEDC) and the NASA Lewis Research Center (LeRC) dedicated to the establishment of a national computational fluid dynamics (CFD) capability.[1] The Boeing Company is also a key contributor to Alliance activities. The NPARC Alliance was formed in 1993 in response to requests from a variety of government, industry, and academic users of the PARC code[2] for a formal organization for the further support, development, and validation of the PARC code. The new code was called NPARC. Version 3.0 of NPARC was released in September 1996.[3]

In 1996, the McDonnell Douglas Corporation (MDC) in St. Louis (now part of Boeing) offered to the NPARC Alliance the CFD technology in their NASTD flow solver and associated software. Also, during this time, efforts were underway at AEDC to consolidate the NPARC and NXAIR codes. The result of the merger of the capabilities of NASTD, NPARC, and NXAIR was the WIND code[4], which became the primary CFD code of the NPARC Alliance. The acronym NPARC was changed to National Project for Applications-oriented Research in CFD to reflect this merger.

The NPARC Alliance is committed to the long-term maintenance of the NPARC flow simulation system, currently embodied in the WIND code. The three main tasks of the NPARC Alliance are ***user support***, ***code development***, and ***code validation***. The *Support Team* coordinates the release of the software, provides training, assists users in its application, and resolves problems. The *Development Team* coordinates enhancements to the code and establishes directions for future development of the code so that the code has the capabilities required by the U.S. aerospace community. The *Validation Team* coordinates the validation of the WIND code to establish a satisfactory confidence level for a wide variety of flow conditions and geometric configurations. The Validation Team coordinates the establishment of, and maintains, an archive of validation cases.

Validation is a long-term effort, and has been a significant part of the Alliance from its inception. A previous paper described early efforts to validate the NPARC code.[5] The present paper discusses the current status of the Validation Archive. Policies regarding validation are outlined and the Archive is described. Sample cases from the Archive are shown, but the intent of this paper is ***not*** detailed validation. Rather the focus is the Archive as a whole.

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† Senior Engineer II, Senior Member AIAA
‡ Aerospace Engineer, Inlet Branch, Senior Member AIAA

Policies

Validation Goals

The primary responsibility of the NPARC Validation Team is to validate the NPARC flow simulation system for a wide range of flow parameters and geometric configurations, and to establish an archive of cases that can be accessed by the NPARC Alliance community to support independent assessment of the software's capabilities. The validation effort must establish:

1) the basis upon which confidence in results produced by the NPARC flow simulation system is founded; and

2) the practical limits on the accuracy of predictions for flow phenomena pertinent to aerospace systems.

This effort is of necessity a continuous process driven by changing conditions, such as the availability of new or better experimental data, bug fixes, and the addition of new capabilities to the codes. In addition to improving the credibility of Alliance software, this ongoing effort will help minimize support needs by providing numerous examples of well-executed problems.

Definition of Validation

The term "validation" has been used in a variety of ways in the literature. A new AIAA document[6] distinguishes between validation, verification, and calibration. Verification is said to be "the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model. Validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model."[6] In other words, "verification determines whether the problem has been solved correctly, whereas validation determines whether the correct problem has been solved." Calibration is defined as the "process of adjusting numerical or physical modeling parameters in the computational model for the purpose of improving agreement with real-world data."[6] Within the NPARC Alliance, our primary interest is in comparison with "real-world data," that is, validation, but the lines between validation and verification blur somewhat due to the close relationships between the Validation and Development teams. On the other hand, calibration is not generally considered to be within the scope of the Validation Team. Individual users may perform this function themselves based upon validation results.

For the Alliance validation effort, we will be guided by the following definition, adapted from one given by Mehta.[7]

> *"A code is said to be validated if the following conditions are met: 1) a comparison of computed results with detailed surface and flow field experimental data and/or other well-accepted solutions shows that the code is able to accurately model the critical physics of the flow; 2) the accuracy and limitations of the experimental data are known and understood; and 3) the accuracy and limitations of the code's numerical algorithms, grid density effects, convergence effects, and physical basis are known and understood. The range of applicability of the validated code depends on the range of flow parameters and/or geometric configurations for which the code has been validated."*

Of course, in practice the accuracy and limitations of the experimental data and the computational results cannot be fully "known and understood." In addition, the degree to which the code must "accurately model the critical physics of the flow" will depend on how the results are to be used. These factors will inevitably introduce some blurring of the line between the states of validation and non-validation. Furthermore, we agree with Roache[8] that, in the strictest sense, a "code cannot be validated in any general sense," only a specific calculation or set of calculations. Nevertheless, this definition does serve to provide the necessary philosophy that guides the validation effort.

The NPARC Alliance validation cases that attempt to meet this strict standard will be termed "model" (ideal) cases. Other types of validation studies are termed "example" and "check" cases, primarily distinguished by the level of effort involved, and by the comprehensiveness of the study. These terms are further defined in later paragraphs.

Validation Team

Activities of the validation effort involve the development of validation cases, running of the CFD codes for the cases, and the maintenance of

the Archive. Specific individuals at both AEDC and NASA LeRC have the charter to perform validation work. However, all users of NPARC Alliance codes are encouraged to participate in the validation process by proposing candidate validation problems and submitting documentation and results. The Validation Team consists of all those individuals actively participating in this effort. The team is coordinated by Ken Tatum of AEDC and Julie Dudek of LeRC, but functions with maximum effectiveness when all users accept responsibility to contribute to the validation process.

Validation Guidelines

Validation Team members are allowed to pursue their individual validation studies in whatever way they choose, but are asked to follow specific guidelines for reporting the results. This reduces the "red tape" in performing the work, but helps to ensure consistency of the final reports, thus allowing easier comparisons of diverse efforts. The level of effort pursued by the user determines if the case is to be classified as a "model," "example," or "check" study (see the "Structure of the Archive" section).

The validation report is web-based, and so is written in Hyper-Text Markup Language (HTML). This format allows links to data files stored on the Archive. The intent is to allow viewers to be able to download all the files needed to duplicate a given study. One link should point to a compressed tar file containing these requisite files. A file naming convention exists to ensure consistency in archive contents, described at the following archive web address:

www.lerc.nasa.gov/www/wind/valid/filenames.html

Each report should include most of, or at least many of, the following parts. Following a descriptive title should be an orienting image of the grid and/or flow field. One or two paragraphs should describe the flow conditions, geometry, flow properties, and computational features examined, in tabular form if appropriate. The basis of the comparison (analytical, computational, or experimental) must be stated, and references given when available.

Details of the flow domain definition and boundary geometry should be given in words, with clarifying figure(s). Grid information should include topologies, number, and sizes, with some data given on stretching parameters and wall spacings. Specific, publicly available grid generation codes should be named, or source code should be included in the tar file, if specific to the case. Detailed figures are most helpful.

Initial flow field and flow boundary conditions should be given, in tabular form if extensive. Specific source codes utilized for such are provided in the tar file, or through links to WIND utility codes. The computational strategies for obtaining the solutions should be discussed, including models, algorithms, and acceleration techniques. Input parameters should ideally be both discussed and included as input streams in the tar file. A table is suggested to distinguish the parametric variations.

Description of the actual computations should include the version of the code employed, all special modifications made, and the computer system used. The CPU type, operating system, and number of processors (including parallelization mode) are worthwhile data. Convergence histories (for steady-state problems) or time histories (for unsteady cases) can be plotted, and discussions of the stopping criteria, number of restarts, etc. should be included. For turbulence models, convergence of turbulence quantities should be discussed.

Comparisons must be presented between the final solutions and the analytical, experimental, and/or computational bases of the case. Experimental uncertainties should be noted, both quantitatively and graphically. Post-processing codes, techniques, and command files should be included for completeness, along with plots showing direct comparisons. When possible, WIND results should also be compared to previous NPARC solutions. Differences should be discussed. Sensitivity studies for model cases should include, as a minimum, grid convergence studies; the Grid Convergence Index method of Roache[8] is proposed as a standard means of evaluating and reporting such grid sensitivity.

NPARC Validation Web Site

The policies, plans, and results of the validation effort are intended to be publicly available as a service of the NPARC Alliance to the entire CFD community. Toward this end, the NPARC Alliance Validation world-wide-web (WWW) site was established to provide this information. The address for the web site is

www.lerc.nasa.gov/www/wind/valid/validation.html

and is linked from the NPARC Alliance home page (www.arnold.af.mil/nparc/index.html).

The policies examine such issues as procedures for conducting and documenting the studies. The plans examine future work for expanding the Archive. The annual NPARC Alliance Policy and Plans document[9] provides further yearly details.

The Validation Archive presents information regarding individual validation cases using the guidelines just described. Accordingly, template web pages (HTML files) have been established and published as a link from the Archive page, which illustrates the application of the guidelines. The web format allows display of text, tables, and images, and allows the organization of the data on multiple pages, if so desired. Further, links to data files allow the download of experimental data, input data files, grid files, solution files, and post-processing files. The reader can explore the case as deeply as desired, or can simply read a short overview.

Structure of the Archive

Web-Based Archive

The Archive itself consists of web pages containing information on the validation cases and "lessons learned" pages which collect unique information regarding the usage of the WIND code. The former provides links to Abstracts of the cases, a Table of the cases, and a Feature Cross-Reference Table. The latter is a regularly updated list of problems, AND their solutions.

Cases

A "case" represents a single geometry and/or flow condition. Validation cases with currently documented studies are listed in Table 1. Cases in progress, include an oscillating airfoil, a combustion case, and a store separation case.

For each case, a general description of the geometry and flow-field characteristics is provided. The data used for comparison with the computed results are described along with links which allow the data files to be downloaded. The comparison data may be analytical, experimental, or computational. References are listed to provide more information on the comparison data.

Table 1: Archive Validation Cases

Supersonic Wedge
Laminar Flat Plate
Turbulent Flat Plate
RAE Transonic Airfoil
S-Duct
Subsonic Diffuser
Supersonic Axisymmetric Jet Flow
Backward-Facing Step
Glancing Shock/Boundary Layer
MADIC 2D Axisymmetric CD Nozzle
Driven Cavity
Re-entry Vehicle
Shock Tube
Hypersonic Cylinder
Hypersonic Ramp
Ejector Nozzle
Transonic Diffuser
ONERA M6 Wing
NLR Airfoil with Flap

"Unit" and "Configuration-Oriented" Cases

A case may be categorized as either a "unit" or "configuration-oriented" case according to the complexity of the geometry and flow field involved. Unit cases are aimed at evaluating a code's ability to predict fundamental fluid dynamic phenomenon; they tend to focus on a single fluid flow feature. Examples include Falkner-Skan flows, flat-plate boundary layers, vortex flows, and shock/boundary-layer interactions. Configuration-oriented cases are aimed at demonstrating the usefulness of a code in supporting the design and analysis of realistic aerospace systems. Examples include airfoil cascades, propulsive system forebody/inlets and nozzle/aftbody combinations, and moving-body trajectory problems.

Study

Within a case there may be one or more "studies." A study may be categorized as "check," "example," or "model" depending on the level of the validation performed and the intent of the study. Each study may also correspond to different individuals performing different studies on the same case, and/or results from other CFD codes. Thus the Archive allows, and encourages, the submittal of validation results obtained by individuals who use other codes. In this manner,

the Archive serves as a forum for the validation and comparison of CFD codes. Of particular interest is comparison of results from WIND with its direct predecessor within the Alliance, the NPARC code, to facilitate user transition to the newer flow solver.

Check Study

A check validation study tests the functionality of newly installed and/or modified code. The primary intent of check studies is to provide the Development Team with a tool to ensure the integrity of all cursory aspects of code operation. At least one of these studies will be an installation check study that is intended for use by new recipients of the WIND code to verify that the code has been properly installed on their computer system. Check studies will be developed, documented, and maintained in conjunction with the Development Team.

Example Study

An example validation study addresses the following primary goals: 1) provide users with quick, but limited validation of the WIND code over a wide range of flows, and 2) provide the new user with clear examples of how to properly set up and execute WIND for a variety of geometries and flow conditions. These studies are indicative of the capabilities of WIND, but do not meet the formal definition of validation in that they do not examine in detail the sensitivity of the results to various input parameters. Example studies will be developed, documented, and maintained in coordination with the Support Team. The example studies also help to minimize the need for users to seek help from the NPARC Alliance Support Team.

Model Study

A model validation study attempts to satisfy the formal definition of validation, as discussed previously. Such studies must, by definition, be more in-depth than either example or check cases. Often, but not always, these concentrate on "unit" problems in order to assist the Development Team in verifying the correct implementation of new features and algorithms. A well-documented model study is a significant aid in debugging a large, complex code.

An important feature of a model study, not usually found in example and check studies, is the examination of "sensitivities" to various user options. Such "options" include, but are not limited to, grid density and clustering, use of turbulence models, choice of artificial viscosity/dissipation models, and flux algorithm/limiting schemes. The accuracy and limitations of each, in isolation or in conjunction with other code features, must be investigated in order to provide users with confidence in their results.

Lessons Learned

A relatively new feature of the Archive is a "Lessons Learned" page (www.arnold.af.mil/nparc/lessons_learned/index.html), also accessible as a link from the NPARC home page. This section attempts to document unique bits of information learned while executing the WIND validation cases. The formal documentation of every nuance and feature of a large, complex CFD code is an impossible task. The WIND documentation now available on the WWW provides many details on code usage, but cannot answer all user questions. Many answers are obtained through experience as users try the code on new problems. As a supplement to the formal documentation, and to help accelerate the process of training new users, the Lessons Learned document provides a means of listing difficulties that users have encountered, along with the workarounds and fixes that have been devised to circumvent those difficulties.

The Lessons Learned pages will be revised regularly to provide a first look at how to avoid difficulties in using WIND effectively. The data contained therein will be forwarded immediately to the Development Team so they can decide if the difficulty requires a bug-fix or a new development. Thus, the lessons learned may serve as a precursor to an entry in the Development Team's Software Problem Tracking web page.

The Lessons Learned are currently organized according to general categories of boundary conditions, algorithms, operational aspects, and utility codes. A miscellaneous category is also included. For each entry, a short problem description is followed by a symptom description and a solution statement. Entries are kept brief to facilitate rapid browsing and easy reference. The user who submitted each lesson is noted for reference, along with the submittal date and (usually) an associated problem. However, NPARC-support serves as the primary point-of-contact for user questions, and should be contacted for more detailed information, rather than

individual users.
(Email: *nparc-support@info.arnold.af.mil*)

Validation Process

The validation process follows the usual analysis process using CFD, which can be summarized as (1) establish the flow problem, (2) model the geometry and flow domain, (3) generate a grid within the domain, (4) specify initial and boundary conditions, (5) establish the computational strategy with associated input parameters and files, (6) perform the computation, (7) assess completion of the computation, (8) obtain desired flow properties from the computed flow field (post-processing), (9) make comparisons of computed results with appropriate data, and (10) document the results.

Defining and Performing the Computation

Step 1 includes definition of reference flow conditions, but also includes specifying the desired objectives of the analysis. Geometry and domain modeling (step 2) refers to both the shape and the extent of the domain to be analyzed. The grid generation step can be computationally expensive for many problems, and usually requires careful consideration to allow other users to repeat, or mimic, the analysis. Initial and boundary conditions have been shown to have a significant effect on the final solutions.[10] The optimal computational strategy is often dependent on the grid topology and objectives of the analysis.

Performing the actual computation itself might often be considered the heart of CFD. However, for validation purposes it is no more, or no less, important than many other factors. Considerations for this step include the computer and operating system employed, to facilitate assessment of algorithmic speed. Determination that the computation is complete is not a trivial task, often due to the fact that complex systems of nonlinear partial differential equations must be solved. The criteria for this determination should always be reported. Once the problem is solved, there are usually a multitude of ways to inspect, visualize, and analyze the results. Users should take care to produce plots, graphs, pictures, and tables that focus on the goals of the study, and which are consistent with *de facto* standards in the CFD community.

In a model validation study, further computations are performed to understand the sensitivity of the desired flow properties to such things as input and algorithm parameters (e.g., CFL number, time-dependent, space-marching, etc.), grid topology and density, turbulence models, and chemistry models. Thus, the problem solution, or even the entire process, may be repeated to assess various sensitivities. Accuracy sensitivity is crucial, but performance sensitivity can also be important. Production users of a code may be tempted to take shortcuts to improve turnaround time for solution; they would greatly benefit in knowing how to achieve desired accuracies without incurring excessive computation time.

Solution Convergence

A fundamental requirement is that a computation be performed until desired steady-state flow properties remain unchanged with further computation. The discretized (algebraic) equations must also be satisfied to within some tolerance. Unsteady problems, planned for future validation, require a different definition of convergence.

Grid and Topology Sensitivity

Another requirement for a valid result is that the desired flow properties remain unchanged as the grid quality or density is changed, a different topology is applied to the flow domain, or the flow domain itself is modified. In particular, the proximity of upstream, downstream, and far field boundaries may be important.

Validation Documentation

Finally, the results must be well documented and added to the Archive. The documentation for the Validation Archive consists primarily of HTML documents accessed through the web site. This allows easy display of text and images, as well as the capability to download data files. In general, the minimal guideline for documenting validation cases is to provide an individual with enough information to define the flow problem and perform a CFD computation. More specific guidelines have already been given in this paper. Links from the web site allow the download of data files to run WIND computations directly.

Sample Validation Cases

The Validation Archive for the NPARC Alliance has been expanded to cover the increased capabilities (i.e., upwind flux formulas, over-

lapped zones, high-temperature gas models, time-accurate algorithms, etc.) now available to the Alliance through WIND and associated tools. Samples of the validation cases available in the Archive are presented below. These range from simple laminar boundary-layer flow to turbulent flow over a 3D wing. For each case the Archive contains an example study showing how to set up and use WIND for the specific geometry and flow conditions. The following descriptions are brief and are presented as examples of the available cases, not as complete validations. Some of the following are still in progress. Some illustrate capabilities which are available, but not yet validated. More detailed information on these cases can be found in the Archive.

Flat-Plate Laminar Boundary Layer

One case examines the laminar flow over a flat plate at zero angle of incidence. The classical Blasius similarity solution[11] provides data for comparison. The WIND solutions, on a sequence of grids, are for a Mach number of 0.1 and a Reynolds number of 200,000 based on a plate length of 1 foot. The skin friction coefficient C_f was observed to be particularly sensitive to grid spacing, and is presented in Fig. 1. The Blasius solution, shown as symbols at discrete longitudinal locations, is compared with WIND solutions on four grids varying from coarse to extra-fine. The grid spacings were varied by a factor of two, both in the streamwise direction and in the initial spacing normal to the wall. The stretchings in the normal direction were kept the same.

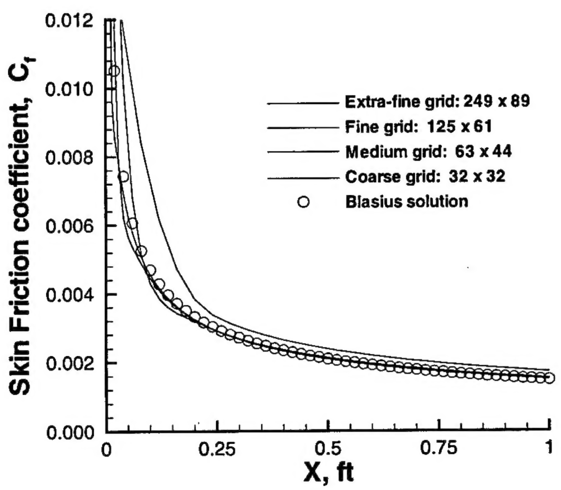

Figure 1. Laminar boundary-layer skin friction coefficient for four grid.

Supersonic Wedge

This case examines the Mach 2.5, inviscid flow over a 15 deg wedge which has an analytic solution.[12] Thus, a point-by-point evaluation of error is allowed. For the model study, we considered the error in the average Mach number behind the oblique shock. A grid convergence study was performed following the procedure of Roache[8] using four successively refined grids; the grid spacing was halved in each direction with each finer grid. The computed grid convergence indices indicated that the errors did decrease to a significant degree with decreased grid spacing and that even the coarse grid was fine enough to ensure that the convergence properties were in range of an asymptotically converging solution. An order-of-accuracy study was performed using the data from the grid convergence study, and showed that the computations were performed with an order of 1.98, which is approximately the spatial second-order accuracy expected from the numerical methods. Two example studies are also available to demonstrate the use of WIND and associated tools for simulating two-dimensional and three-dimensional laminar and turbulent flows about the wedge.

RAE Transonic Airfoil

This case examines the transonic (Mach 0.729), turbulent flow about the RAE 2822 airfoil at an angle of attack of 2.31 deg and a Reynolds number of 6.5 million based on the chord.[13] An example study demonstrates the use of WIND and associated tools for simulating flow about an

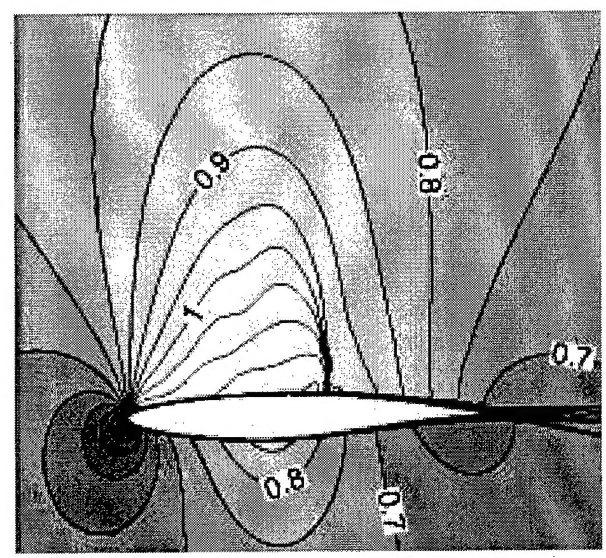

Figure 2. Mach number contours about the RAE 2822 airfoil.

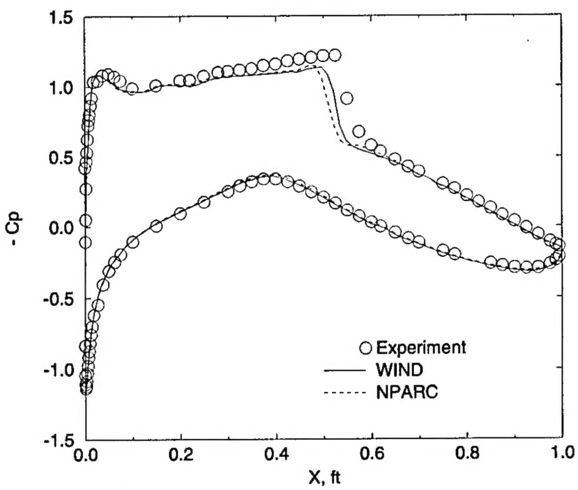

Figure 3. Comparison of pressure coefficients for the RAE 2822 airfoil.

airfoil. Figure 2 shows Mach number contours of the resulting flow field. Note the shock formed on the upper surface. Figure 3 shows comparisons of the pressure coefficients on the airfoil surface between WIND, NPARC, and the experimental data. The WIND results follow the trend of the NPARC results with a slight improvement in the capture of the shock.

ONERA M6 Wing

This case examines the Mach 0.84, turbulent flow over the ONERA M6 wing[14] at an angle of attack of 3.06 deg and a Reynolds number of 11.2 million based on the mean aerodynamic chord. An example study demonstrates the use of WIND and associated tools for simulating flow about a 3D wing. Figure 4 shows the geometry of the wing, along with the computed pressure contours on the surface of the wing and the symmetry plane. This study also includes comparisons between the computed and experimental values of the surface pressure coefficients. Experimental uncertainties of ±0.012 psi are given for the pressure transducers employed to obtain the reference data.[14]

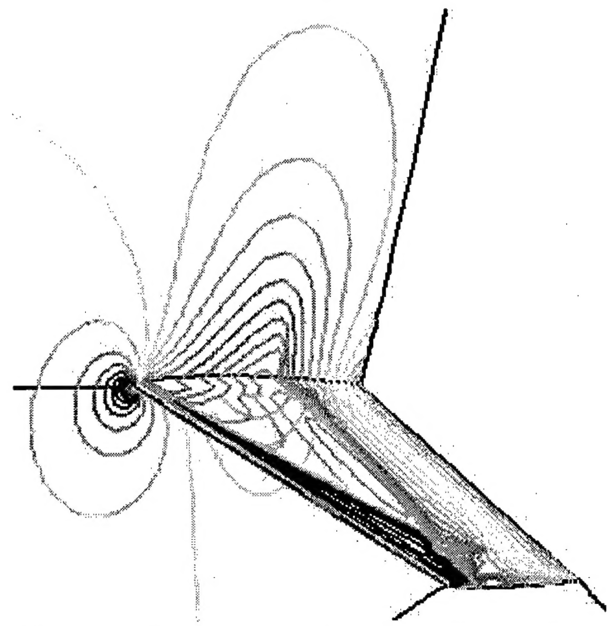

Figure 4. Pressure contours on the surface and symmetry plane of the ONERA M6 wing.

NLR Airfoil with Flap

This case examines the Mach 0.2, turbulent flow over an airfoil at an angle of attack of 10 deg with a trailing edge flap, and illustrates the Chimera capability of WIND. The single-zone C-grid about the flap overlaps, and is completely contained within, the single-zone C-grid about the airfoil. Figure 5 shows the geometry and over-

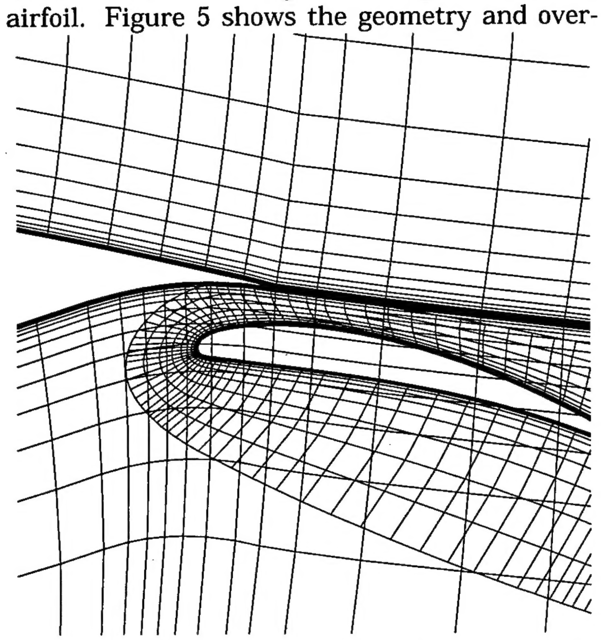

Figure 5. Overlapped grid in the region of the trailing edge of the airfoil with a flap.

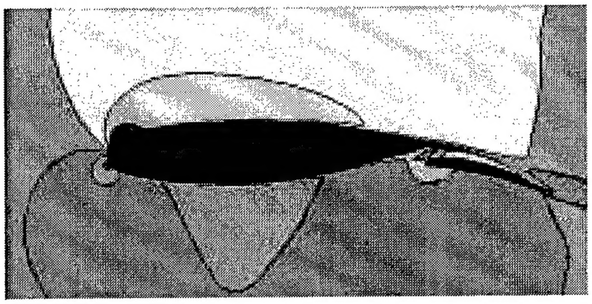

Figure 6. Subsonic Mach number contours about an airfoil with a flap.

lapped grids near the trailing edge. An example study demonstrates the use of a WIND utility to create the hole and the fringe points to define the boundary conditions for the overlapping grid points. Figure 6 shows the geometry of the entire airfoil and flap, along with the Mach number contours of the flow field in the region of the airfoil and flap.

Hypersonic Ramp

This case examines the Mach 7.0, laminar viscous flow of air with a static pressure of 14.7 psi and a static temperature of 520°R over a 15 deg ramp. An example study examines the use and influence of different gas models available in WIND: calorically perfect air (single species), thermally perfect air (2 species, frozen), equilibrium air (Liu-Vinokur curve fit, single species), and nonequilibrium air with finite-rate chemical reactions (5 species). Further, since the flow is supersonic and non-separating, the space-marching capability of WIND to solve the parabolized Navier-Stokes equations can be demonstrated. Figure 7 shows the temperature distributions along the ramp for the various models. As can be seen, the flow does involve some high-temperature effects that alter the thermodynamic behavior of the air.

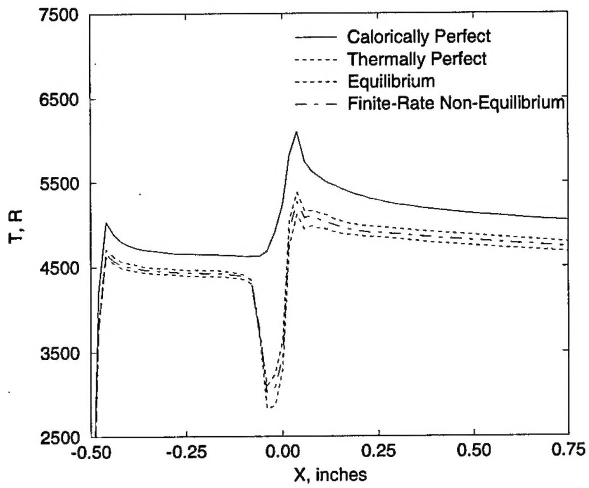

Figure 7. Temperature along the surface of a 15 deg ramp at Mach 7.0.

Shock Tube

This case examines the unsteady, inviscid, axisymmetric flow in a shock tube. An analytic solution is available[12] for the flow conditions at a specified time after the diaphragm bursts. The unsteady flow solution was computed by WIND in a time-accurate manner using explicit time-marching methods, given the initial flow state prior to the bursting of the diaphragm. Figure 8 shows the density distribution with comparisons between WIND, NPARC, and the analytic solution. WIND shows a slight improvement in the capturing of the contact discontinuity and the shock with minimal oscillations.

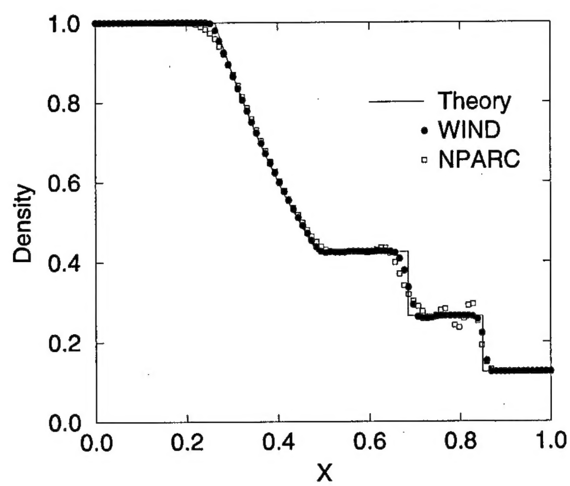

Figure 8. Density distribution along the shock tube.

Summary and Conclusions

A publicly available, web-based Validation Archive has been created for the validation of the WIND code and as a forum for use by the entire CFD community. This archive is maintained by the NPARC Alliance as an important part of its effort to establish a national computational fluid dynamics capability. The CFD community must have a satisfactory confidence level in WIND for it to ever become a credible national resource. Continued maintenance of the Archive is essential to this goal.

No one individual, or even a small team of individuals, can be fully responsible for all the capabilities of a modern CFD code. Guidelines are given herein for performing validation studies, and for documenting them for submittal to the Archive. AEDC and NASA LeRC have taken the lead in performing studies, and for publishing and maintaining the Archive on the WWW. However, all WIND users are requested to be part of the team that generates the Archive. Furthermore, the Archive is not considered to be a static entity, either in terms of content or in terms of policy and practice. Improvements are continually sought which will make the Archive more useful to the CFD community.

Studies consist of CFD solutions obtained using WIND and related codes, particularly those codes with capabilities which the Development Team intends to add to WIND. Comparisons of CFD solutions, analytical solutions, and experimental data are available on the web for a wide range of problems. Sensitivity studies are important in performing complete, or model, validation studies. Sample validation studies are described to illustrate the value of the Archive.

Acknowledgments

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References

1. Matty, J. J. and Shin, J., "The NPARC Alliance: A Progress Report." AIAA-97-3353, 1997.

2. Cooper, G. K. and Sirbaugh, J. R., "*The PARC Code: Theory and Usage.*" AEDC-TR-89-15, December 1989.

3. "*NPARC Version 3.0 User's Manual.*" September 1996.

4. Bush, R. H., Power, G. D., and Towne, C. E., "WIND: The Production Flow Solver of the NPARC Alliance." AIAA-98-0935, January 1998.

5. Towne, C. E. and Jones, R. R., "Results and Current Status of the NPARC Alliance Validation Effort." AIAA-96-0387, January 1996.

6. *Guide for the Verification and Validation of Computational Fluid Dynamics Simulations.* AIAA G-077-1998.

7. Mehta, U. B., "Computational Requirements for Hypersonic Flight Performance Estimates." *Journal of Spacecraft and Rockets*, Vol. 27, No. 2, pp. 103-112, 1990.

8. Roache, P. J., "Perspective: A Method for Uniform Reporting of Grid Refinement Studies." *Journal of Fluids Engineering*, Vol. 116, September 1994.

9. NPARC Alliance. *NPARC Alliance Policies and Plans.* August 1998.

10. Rudy, D. H. and Strikwerda, J. C., "Boundary Conditions for Subsonic Compressible Navier-Stokes Calculations." *Computers and Fluids*, Vol. 9, pp. 327-338, 1981.

11. White, F. M., *Viscous Fluid Flow.* McGraw-Hill, Inc., New York, 1974.

12. Anderson, J. D., *Modern Compressible Flow.* McGraw-Hill, Inc., New York, 1984.

13. Cook, P.H., McDonald, M. A., and Firmin, M. C. P., "Aerofoil RAE 2822 - Pressure Distributions, and Boundary Layer and Wake Measurements." *Experimental Data Base for Computer Program Assessment.* Report of the Fluid Dynamics Panel Working Group 04, AGARD Report AR 138, May 1979.

14. Schmitt, V. and Charpin, F., "Pressure Distributions on the ONERA-M6-Wing at Transonic Mach Numbers." *Experimental Data Base for Computer Program Assessment.* Report of the Fluid Dynamics Panel Working Group 04, AGARD AR 138, May 1979.